Bank Erosion and Structure Stability in Combined Ship and Wind Waves

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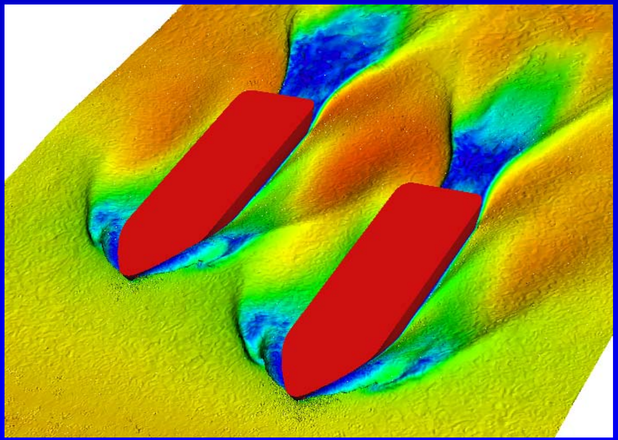
Ship Wake Challenges

- Ship-induced wave modeling
- Ship wave – wind wave interaction
  - Wind waves are irregular, use statistical representation, assume stationarity, continuous history for each storm
  - Ship wakes are regular, episodic, use wave-by-wave analysis, water levels can change dramatically during single event
- Bank stability
  - Water level changes
  - Life cycle loading
  - Frequency of ship and wind wave

Ship Wake R&D Needs

- Wake Empirical and Numerical Models
- Bank Erosion Model
  - Wake/wind wave height, wave period, wave direction, water depth, water level on structure, wave travel distance, number of waves, bank material properties
  - Primary waves, secondary waves, high speed vessels, multiple vessels
  - Conservation of energy in surf zone for cross shore transport
  - One line model for longshore transport
- Bank/Structure Stability Model
  - Similar parameter list
  - Hudson or Shields stability approach
  - Damage over life cycle



Portland, Oregon, 2001

Wales, UK, 2002

Coastal Structure R&D

- Incipient motion and initial damage of armor stone
- Rubble mound structure damage progression
  - **Developing breakwater, jetty, and revetment deterioration models for used life cycle analysis**
- Risk Analysis of Coastal Structures
  - **Developed STORM-CSHORE – a life-cycle simulation tool**
- Gravel beach transport

Initial Damage

$$\frac{H_s}{\Delta D_{n50}} = (K_D \cot \alpha)^{1/3}$$

Damage Prediction on Stone Armor

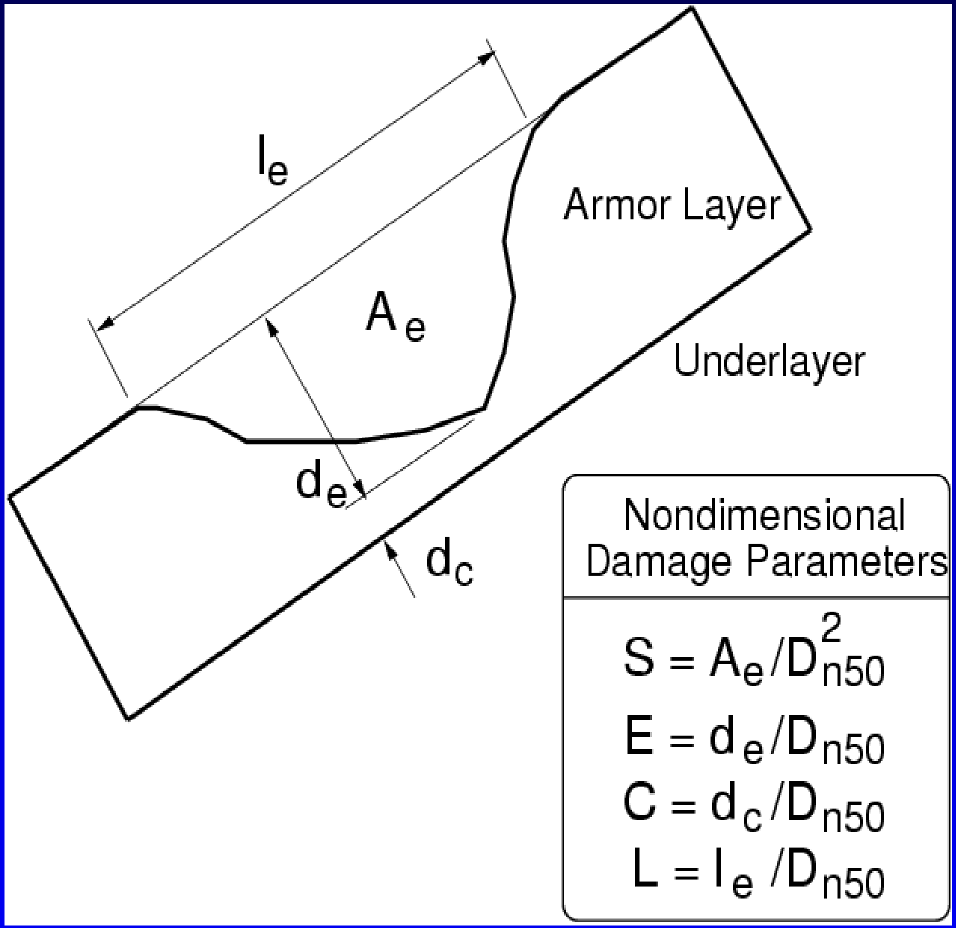
- Melby and Kobayashi 1998-present

Shape of Damaged Profile

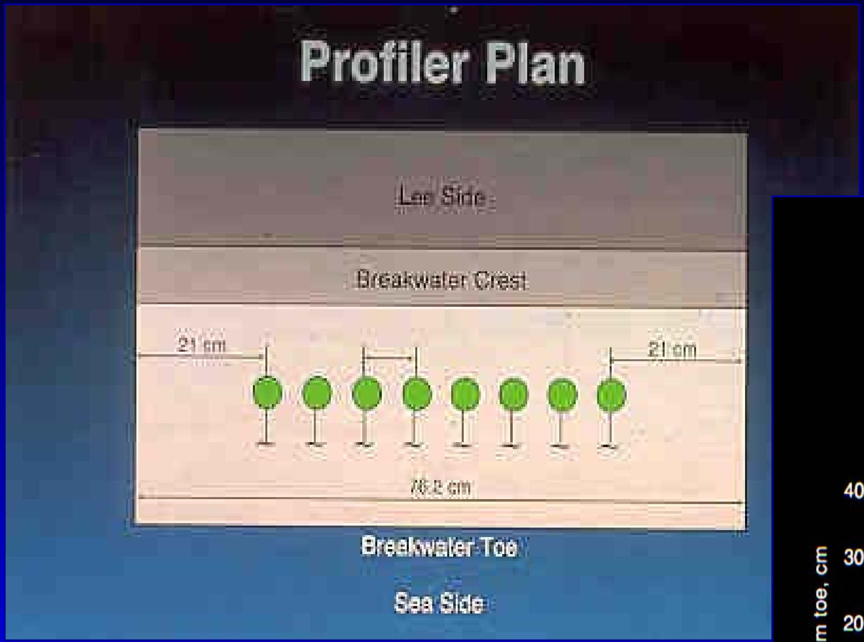
$$\overline{E} = 0.46\sqrt{\overline{S}}$$

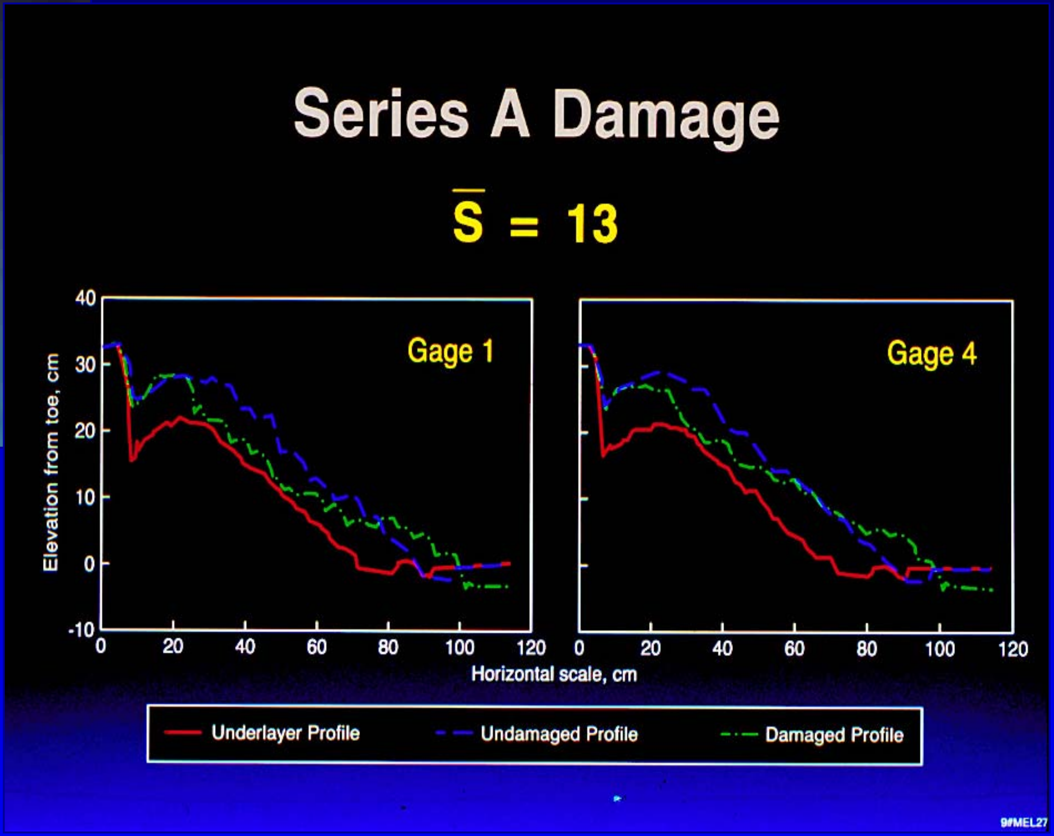
$$\overline{C} = \overline{C}_o - 0.1\overline{S}$$

$$\overline{L} = 4.4\sqrt{\overline{S}}$$



Damage Profiles





US Army Corps of Engineers

Engineer Research and Development Center

Stone Damage Classification

- **Initial Damage**: "no damage" value in 1984 SPM...D = 0-5% displacement by volume or S = 0 - 2 by profiles
- **Intermediate Damage**: S = 2 - 12
- **Failure**: Underlayer exposed through a hole at least D_{n50} in diameter, $D \geq 20\%$, S = 8-20

SOUTHWEST PASS, LA

DAMAGE DEFINITIONS

- PROFILING OR DISPLACED AREA METHOD
  - Eroded Volume: Hudson, Jackson, *D*%, active region
  - Eroded Area: Broderick and Ahrens, $S = A_e/D^2_{n50}$
  - $0.6 < S/D\% < 1.25$
  - If $S/D\% = 0.8$, then $D = 5\%$ corresponds to $0 < S < 4$
  - Note that *S* determined from average profile can be very different from average *S* of several profiles

Damage Progression

Eroded Area Prediction

$$\overline{S}(t) = \overline{S}(t_n) + 0.025(N_s^5)T_m^{0.25}(t^{0.25} - t_n^{0.25}) \quad for \quad t_n \le t \le t_{n+1}$$

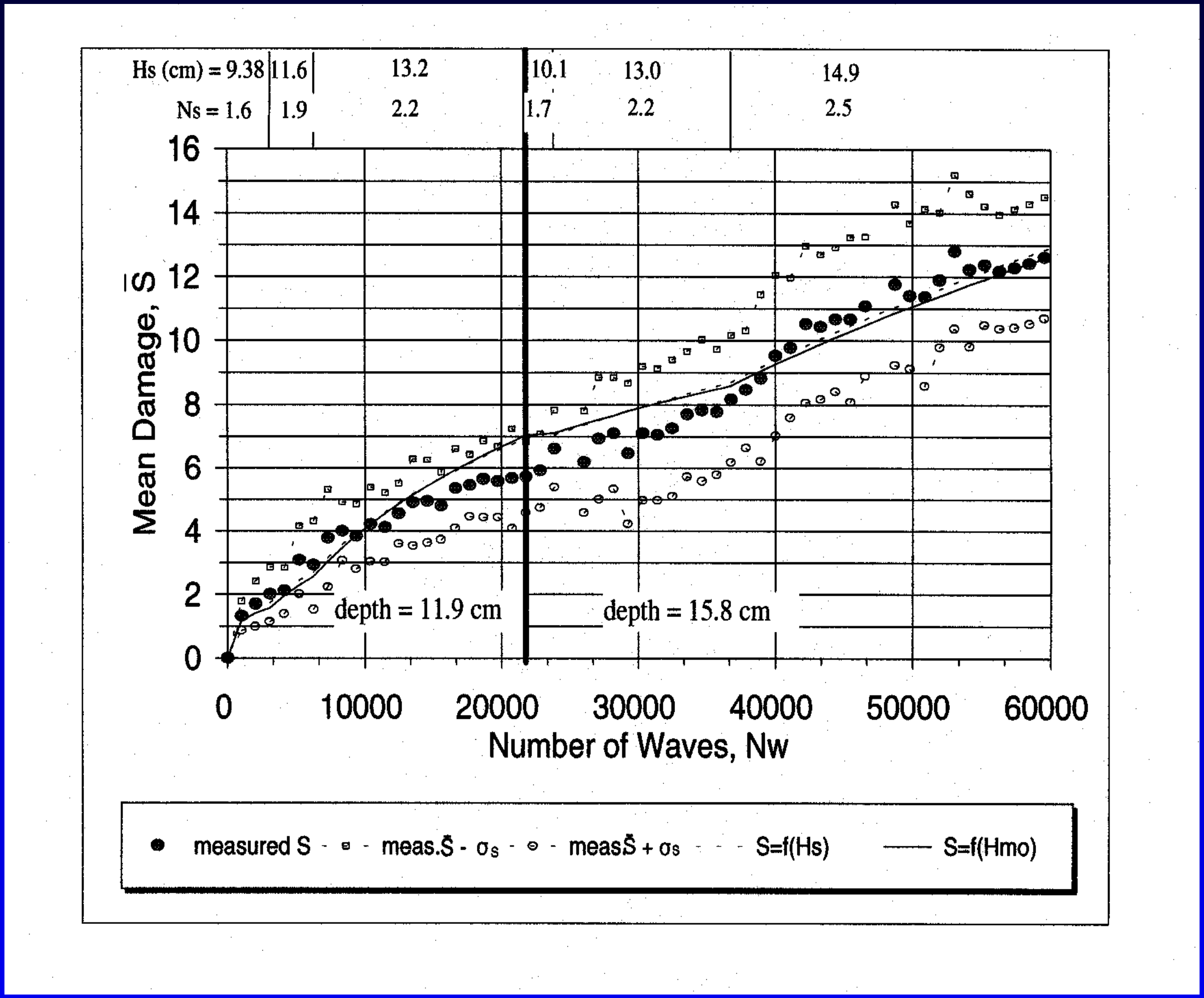
$$\overline{S}(t) = \overline{S}(t_n) + 0.022(N_{mo}^5)T_p^{0.25}(t^{0.25} - t_n^{0.25}) \quad for \quad t_n \le t \le t_{n+1}$$

$$\sigma_s = 0.5S^{0.65}$$

Standard Deviation shows cross-shore variation

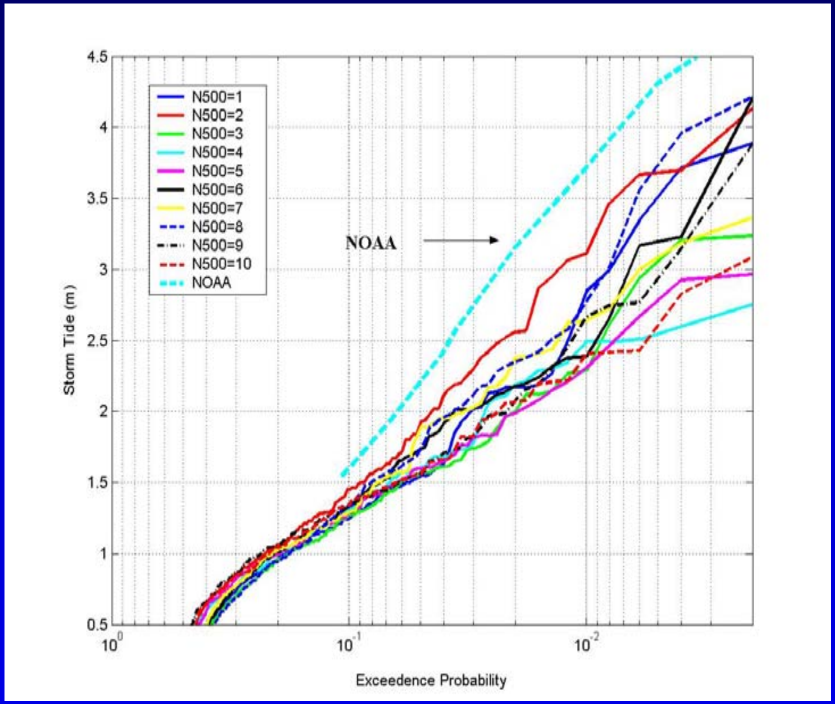
$$S = \frac{A_e}{D_{n50}^2} \qquad N_s = \frac{H_s}{\Delta D_{n50}} \qquad N_{mo} = \frac{H_{mo}}{\Delta D_{n50}}$$

Damage Prediction



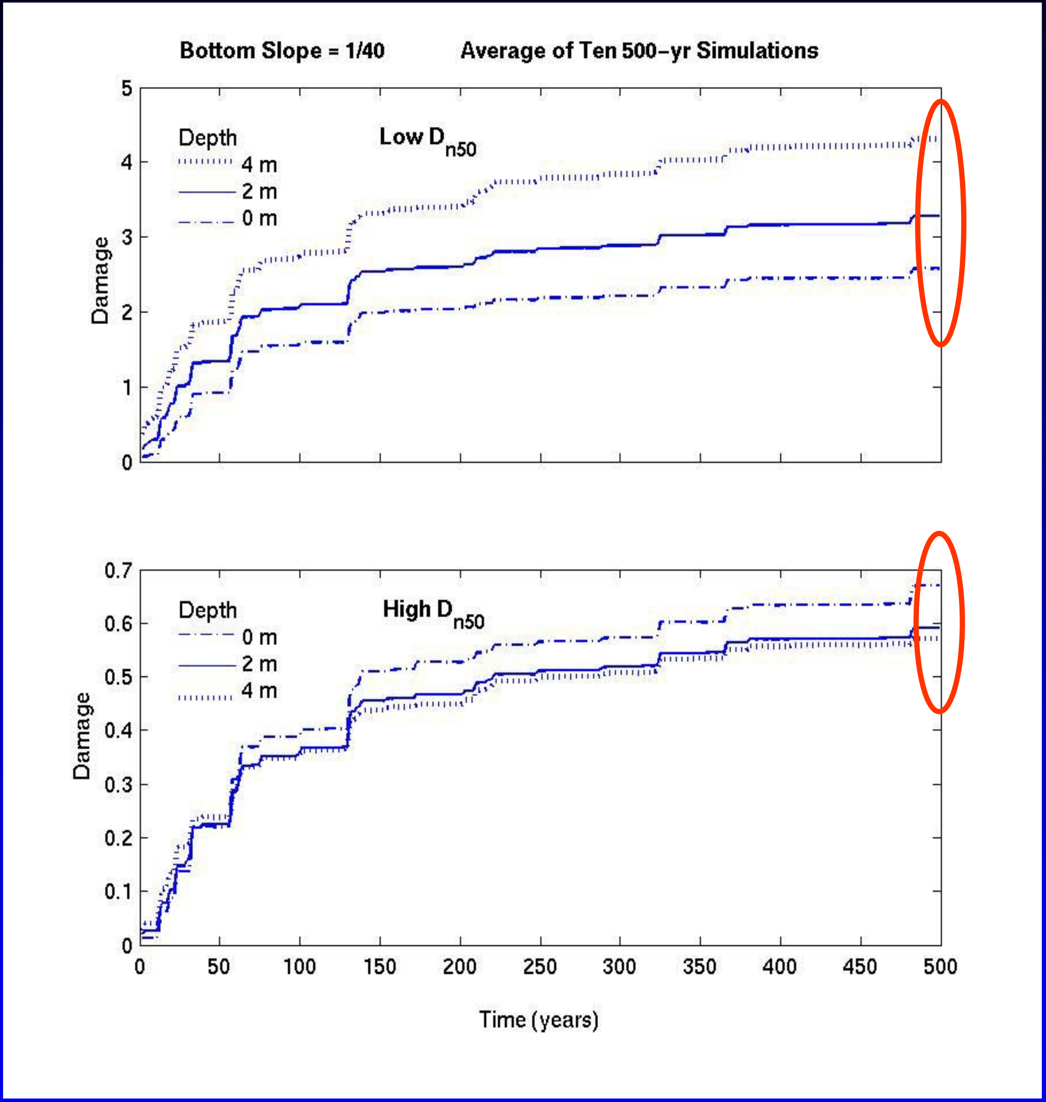
STORM-CSHORE

- Incorporated simulation capability to permit life-cycle analyses of structures
- Predicts storms at coast, total water depth (wave setup, storm surge, tide), wave height at any location
- Predicts damage and overtopping
- Predicts mean and variability



AVERAGE OF TEN 500-YR SIMULATIONS

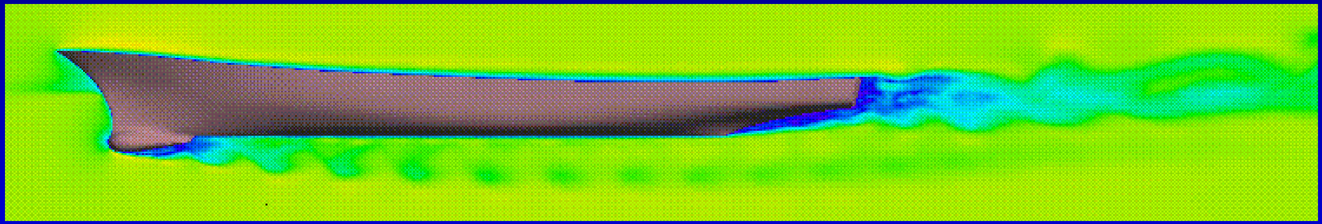
Comparison of Average Damage Progression

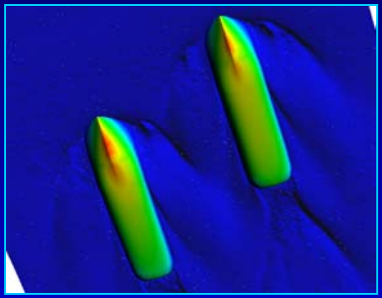


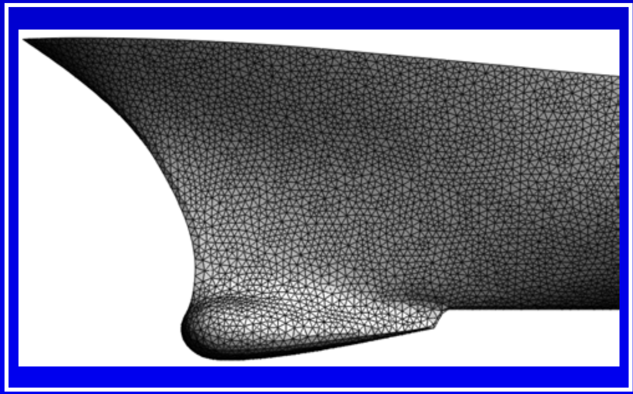
Combined Wind Wave and Ship Wake Damage

- Simplest solution would be to superimpose number of ship-induced waves at given height and period
- Need to know something about probability of occurrence of wakes
- This is a function of ship type, speed, draft, frequency, proximity to structure, etc.

Navier-Stokes Modeling of Ship Wakes







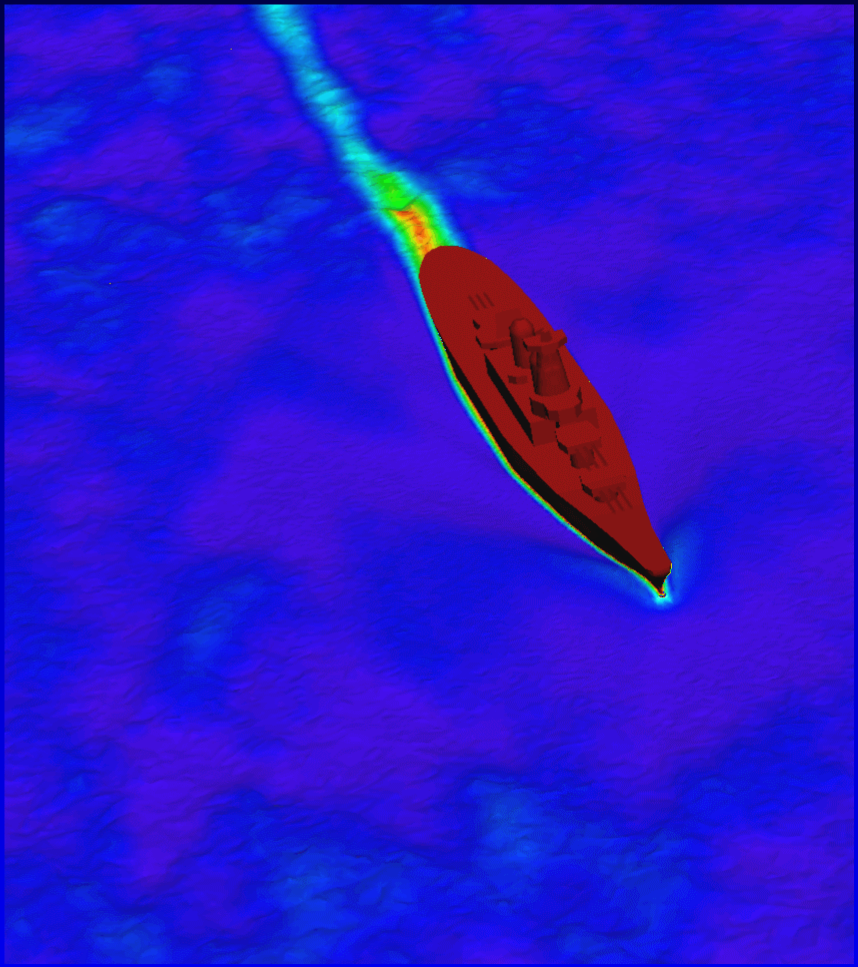
Objective

Develop Fluid-Structure Interaction Technology for Large Scale Simulation of Coastal Problems

- Wave Formation
- Coastal Structure
- Wave Impact
- Ship Hydrodynamics

Challenges

- Nonlinear Navier-Stokes Equations (u,v,w,p)
- Discontinuous Density and Viscosity
- Location of the Free-Surface is an unknown
- Moving Boundaries
- Nonlinear Rigid Body Dynamics, 6DOF
- Moving Mesh Mechanism
- Elasticity Equations for Hawsers and Structures
- Large- Scale Computation



Governing Equations: Navier-Stokes Equations For Both Moving and Fixed Meshes

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} - \mathbf{g}\right) - \nabla\cdot\sigma = 0$$

$$\nabla\cdot\mathbf{u} = 0$$

$$\sigma = -\mathrm{p}\,\mathbf{I} + 2\mu\varepsilon(u)$$

$$\varepsilon = \frac{1}{2}(\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathrm{T}})$$

Stabilized Finite Element Formulations

$$\int_{\Omega} \mathbf{w}^h \cdot \rho \left(\frac{\partial \mathbf{u}^h}{\partial t} + \mathbf{u}^h \cdot \nabla \mathbf{u}^h - \mathbf{g} \right) d\Omega + \int_{\Omega} \boldsymbol{\varepsilon}(\mathbf{w}^h) : \boldsymbol{\sigma}(p^h, \mathbf{u}^h) d\Omega$$

$$+ \int_{\Omega} q_p^h \nabla \cdot \mathbf{u}^h d\Omega + \sum_{e=1}^{ne} \int_{\Omega^e} \tau_c \nabla \cdot \mathbf{w}^h \rho \nabla \cdot \mathbf{u}^h d\Omega$$

$$+ \sum_{e=1}^{ne} \int_{\Omega^e} \frac{\tau_m}{\rho} \left[\mathbf{u}^h \cdot \nabla \mathbf{w}^h - \nabla \cdot \boldsymbol{\sigma}(q_p^h, \mathbf{w}^h) \right] \cdot$$

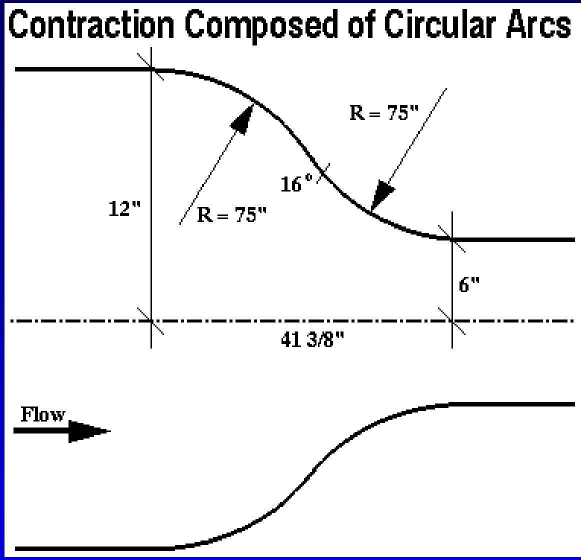
$$\left[\rho \left(\frac{\partial \mathbf{u}^h}{\partial t} + \mathbf{u}^h \cdot \nabla \mathbf{u}^h - \mathbf{g} \right) - \nabla \cdot \boldsymbol{\sigma}(p^h, \mathbf{u}^h) \right] d\Omega = \int_{\Gamma_{h_u}} \mathbf{w}^h . \mathbf{h} \, d\Gamma$$

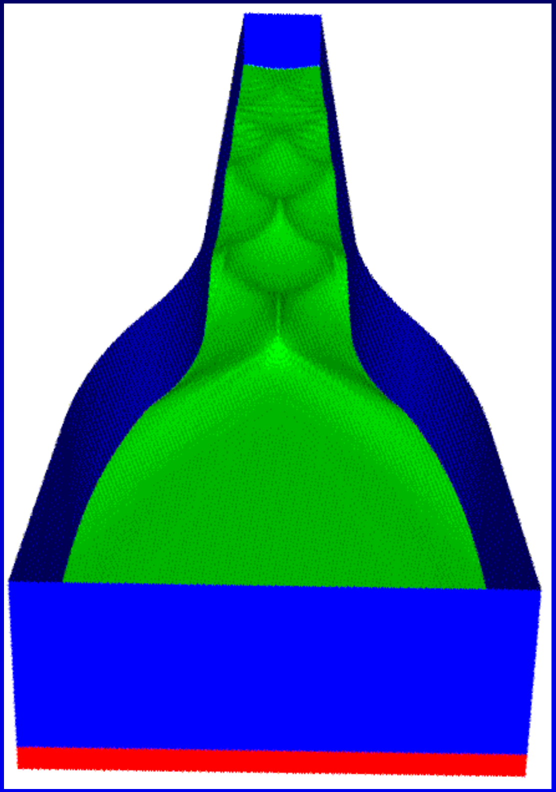
$$\int_{\Omega} \psi^h \left(\frac{\partial \phi^h}{\partial t} + \mathbf{u}^h \cdot \nabla \phi^h \right) d\Omega + \sum_{e=1}^{ne} \int_{\Omega^e} \nu \nabla \psi^h \cdot \nabla \phi^h d\Omega = 0$$

$$\tau_m = \left[\left(\frac{2}{\Delta t} \right)^2 + \left(\frac{2 \| \mathbf{u} \|}{h} \right)^2 + \left(\frac{4\mu}{\rho h^2} \right)^2 \right]^{-\frac{1}{2}}$$

$$\nu = \frac{h \|\mathbf{u}\|}{2}$$

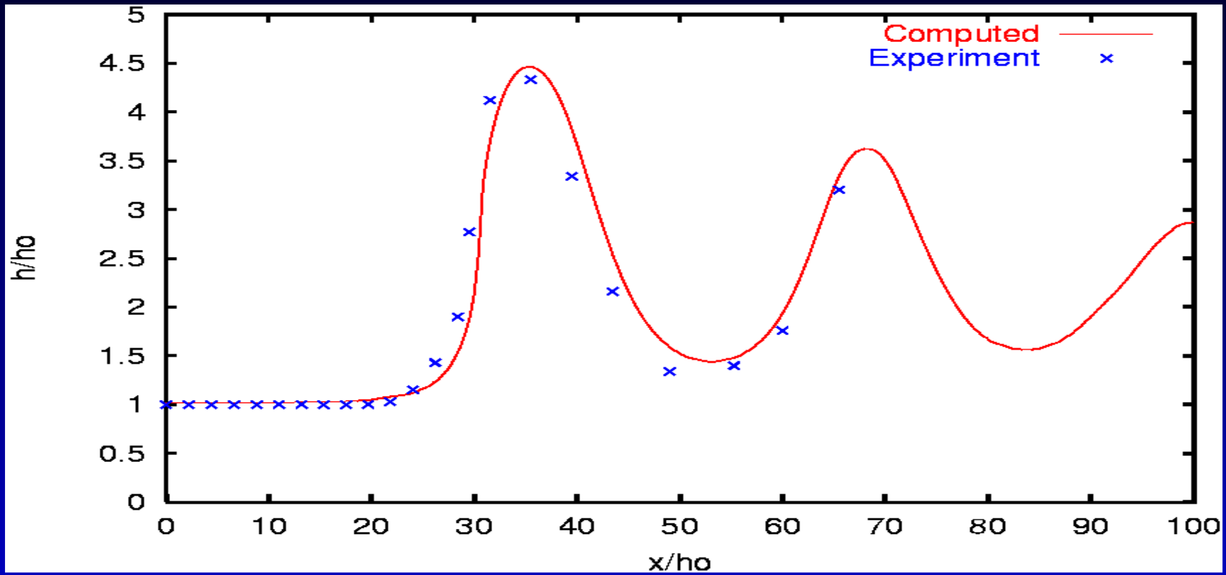
Accuracy of the Method in 3D: Contraction Channel



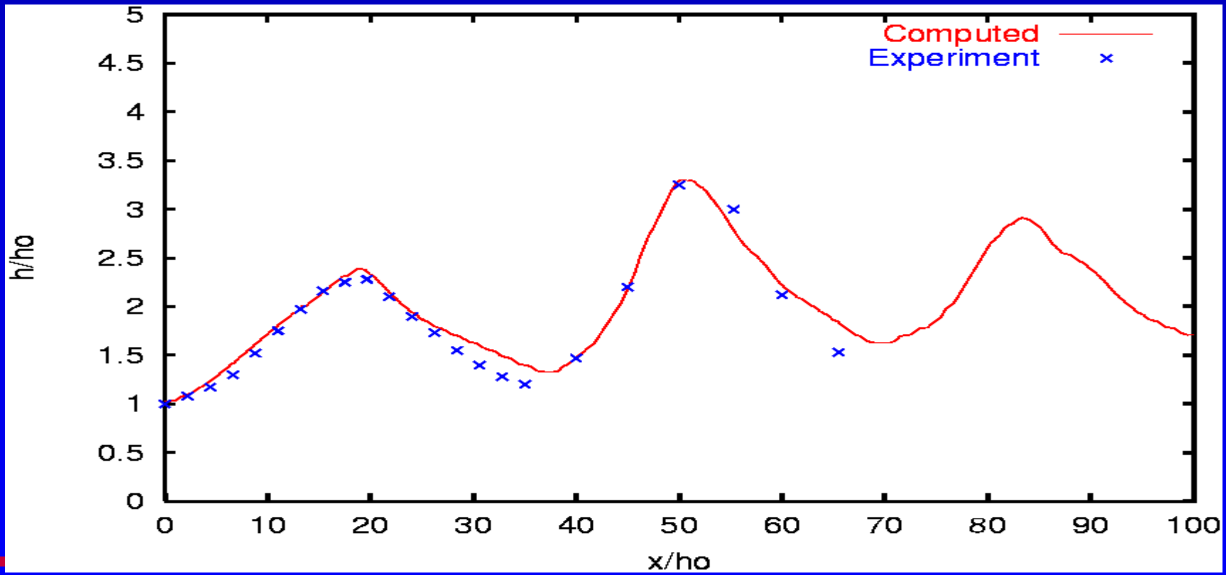


- 401x61x111
- Fr = 4
- Equations: 13 Million

Along the Center

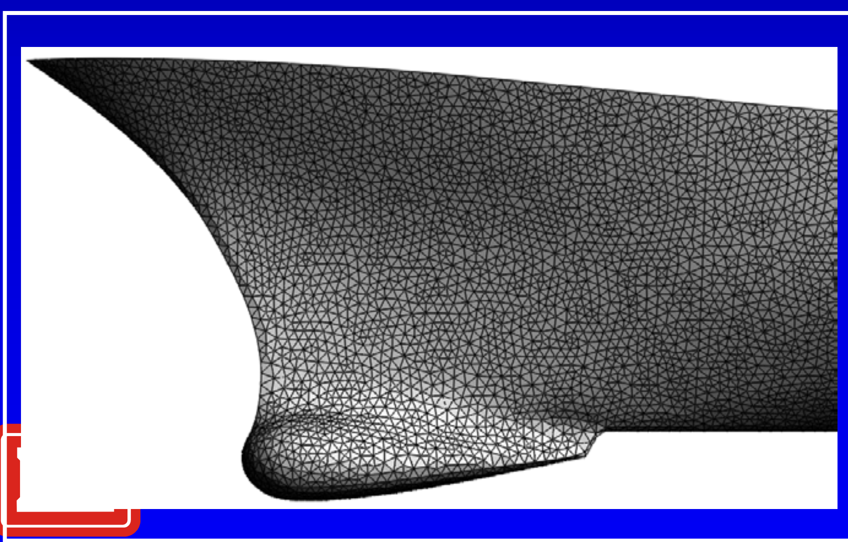


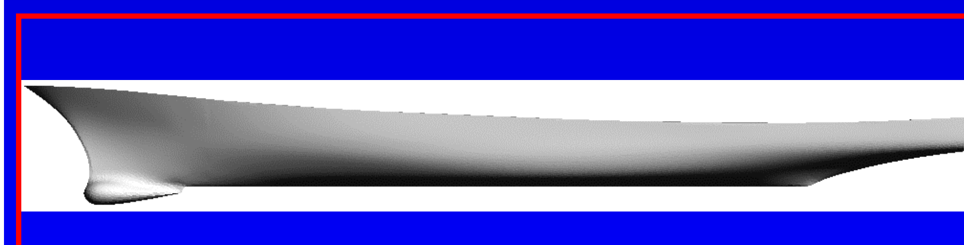
Along the Wall



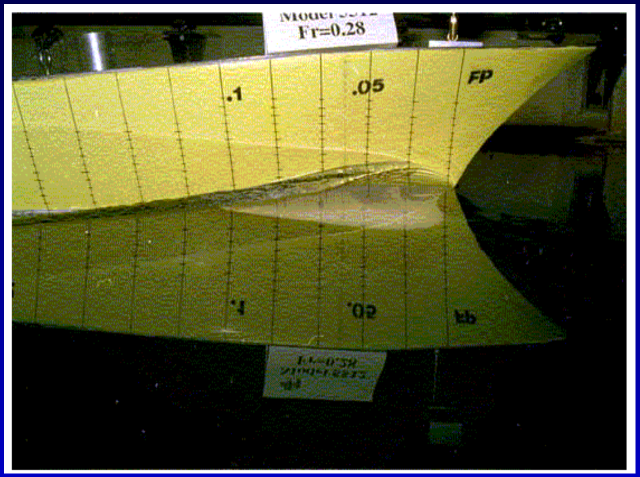
Ship Hydrodynamics – DTMB 5415

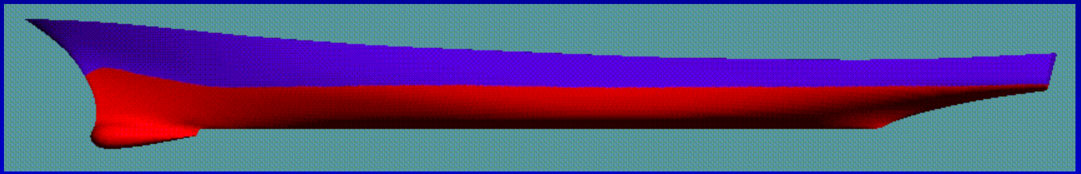
- Code Verification
- Experimental Data Exist
- Fr=0.28 and 0.41
- Mesh: 25 Million Element

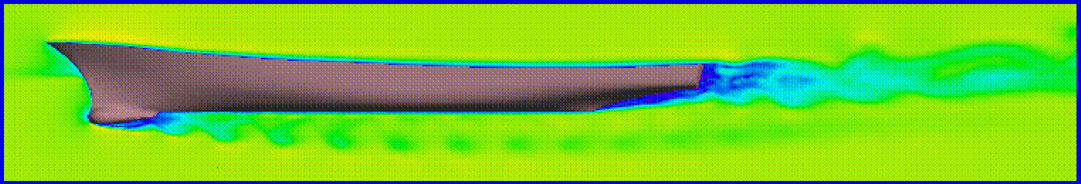


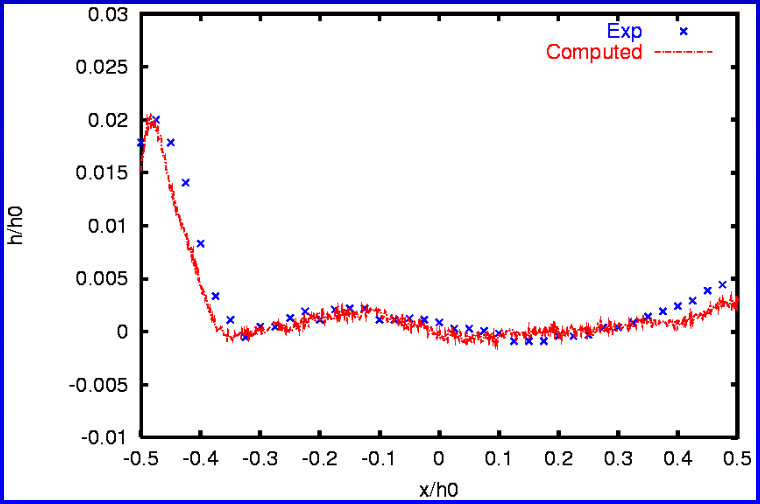


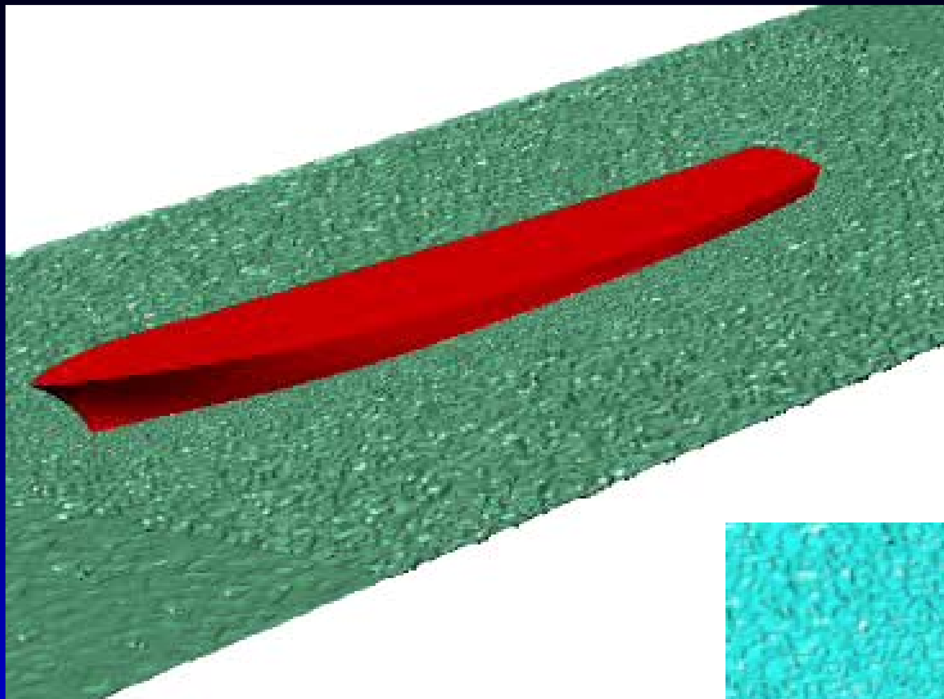
DTMB 5415: Fr=0.28

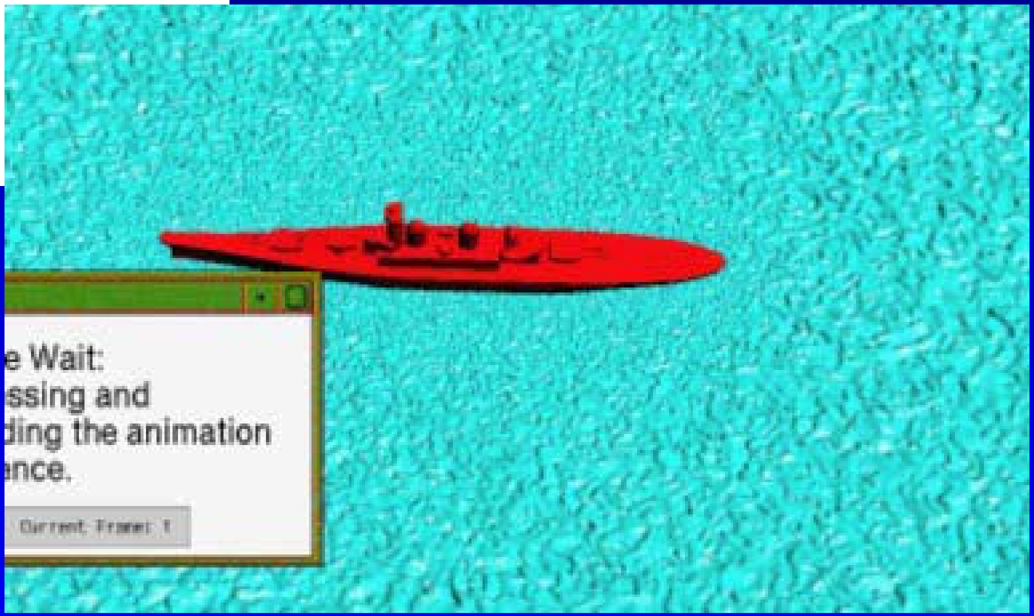








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Governing Equations: Rigid Body Dynamics

$$\mathbf{F}_X - m\,\mathbf{g}_X = m\,\mathbf{a}_X$$

$$\mathbf{M}_Y = \mathbf{J}_Y\,\alpha_Y$$

$$\mathbf{u}_P^{n+1} = \mathbf{v}^{n+1} + \omega^{n+1} \times (\mathbf{r}_P^{n} - \mathbf{C}^{n})$$

$$\mathbf{d}_P^{n+1} = \Delta\,\mathbf{C}^{n+1} + \Delta\theta^{n+1} \times (\mathbf{r}_P^{n} - \mathbf{C}^{n})$$

$$\mathbf{a}^{n+1} = \frac{\mathbf{F}^{n+1}}{m} - \mathbf{g}$$

$$\mathbf{v}^{n+1} = \mathbf{v}^{n} + \Delta t\left(\frac{\mathbf{a}^{n+1} + \mathbf{a}^{n+1}}{2}\right)$$

$$\Delta\,\mathbf{C}^{n+1} = \Delta t\left(\frac{\mathbf{v}^{n+1} + \mathbf{v}^{n+1}}{2}\right)$$

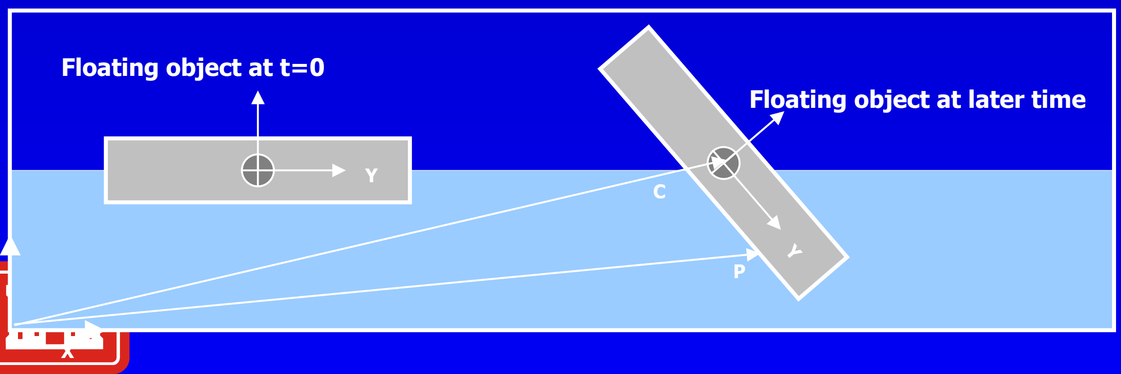
$$\alpha^{n+1} = \mathbf{R}^{n+1}\mathbf{J}_Y^{-1}\mathbf{R}^{n+1^{T}}\mathbf{M}$$

$$\omega^{n+1} = \omega^{n} + \Delta t\left(\frac{\alpha^{n+1} + \alpha^{n}}{2}\right)$$

$$\Delta\theta^{n+1} = \Delta t\left(\frac{\omega^{n+1} + \omega^{n}}{2}\right)$$

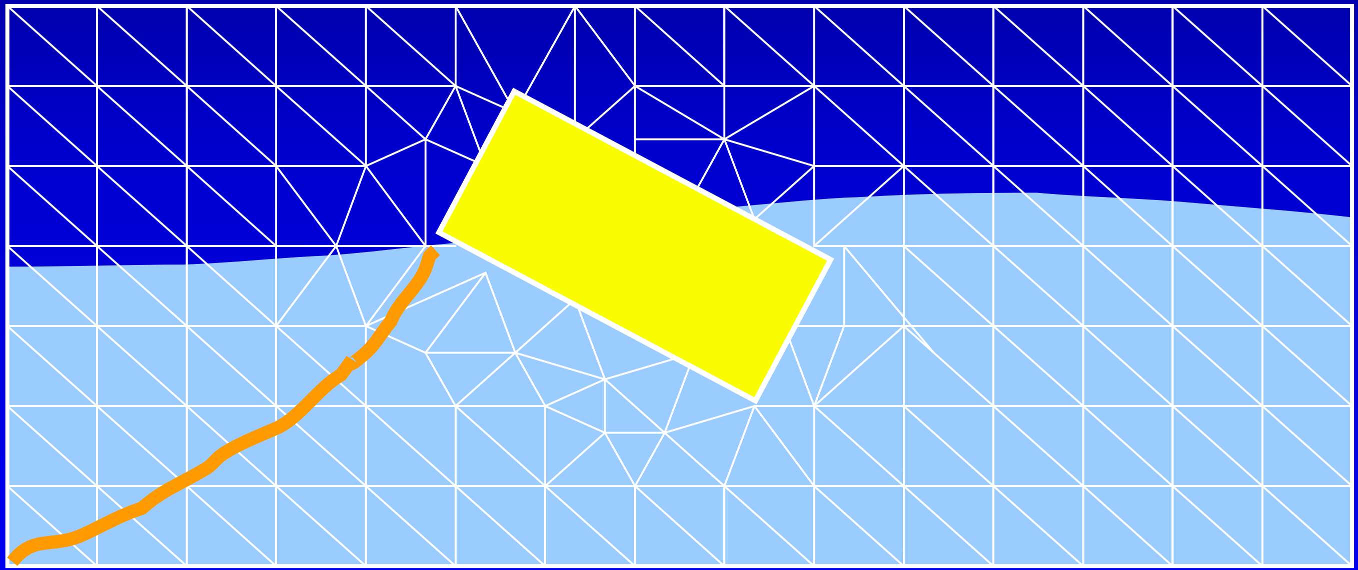
$$\text{Compute } [\mathbf{S}] \text{ based on } \Delta\theta_1^{n+1}, \Delta\theta_2^{n+1}, \Delta\theta_3^{n+1}$$

$$\mathbf{R}^{n+1} = \mathbf{S}\mathbf{R}^{n}$$

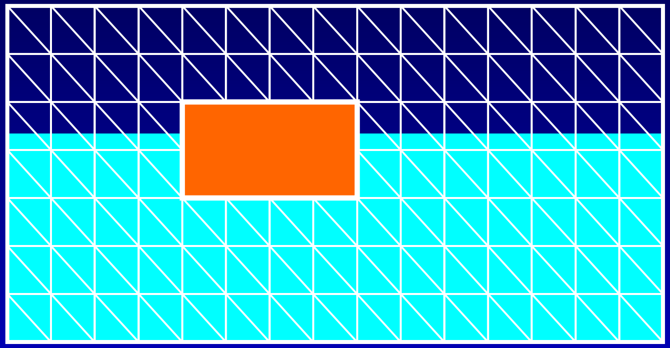


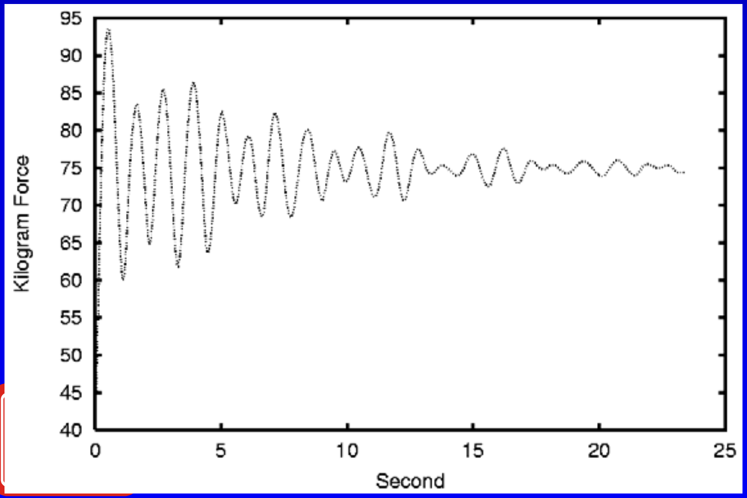
Governing Equations: Cables

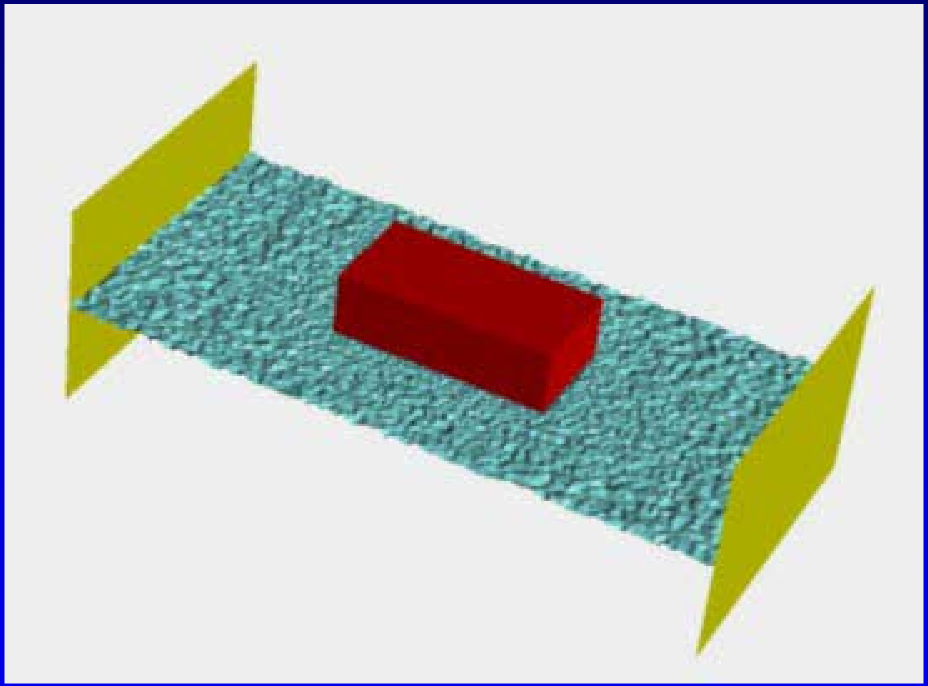
$$\mathbf{F}_{\text{cable}} = EA\frac{\langle L_f \text{-} L_i \rangle}{L_i}\hat{\mathbf{e}} \qquad \langle L_f \text{-} L_i \rangle = \begin{cases} L_f \text{-} L_i & L_f > L_i \\ 0 & L_f < L_i \end{cases}$$



6 DOF Example: Dropping Box in Water

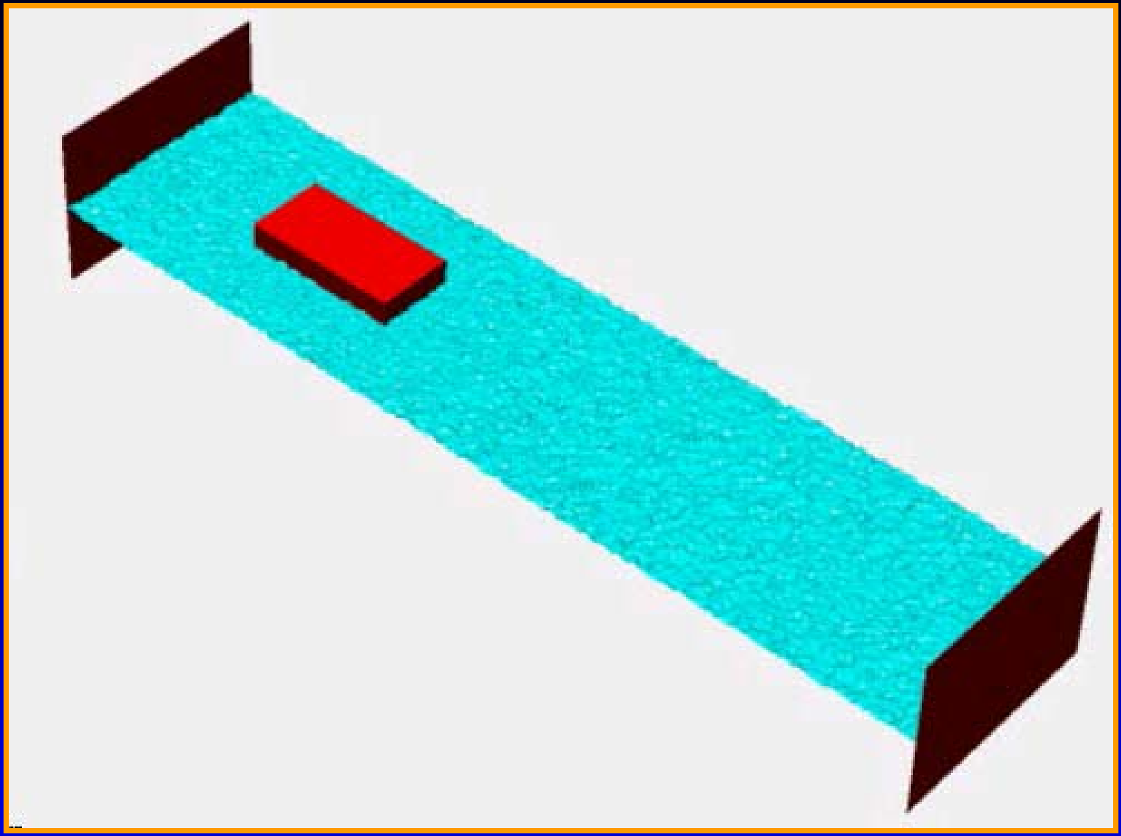


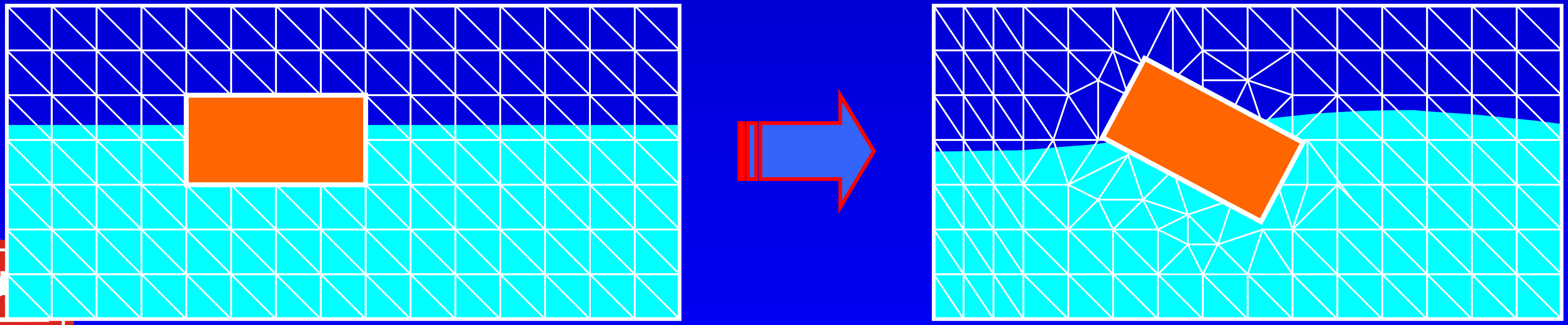




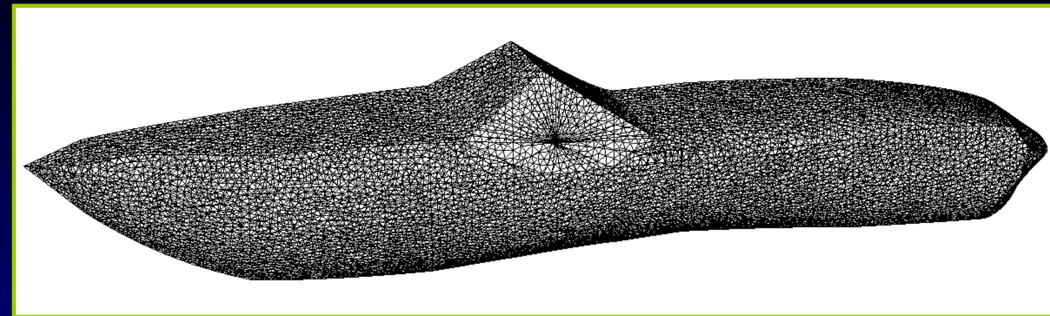
Wave Generator And 6 DOF Example:

Drifting Object

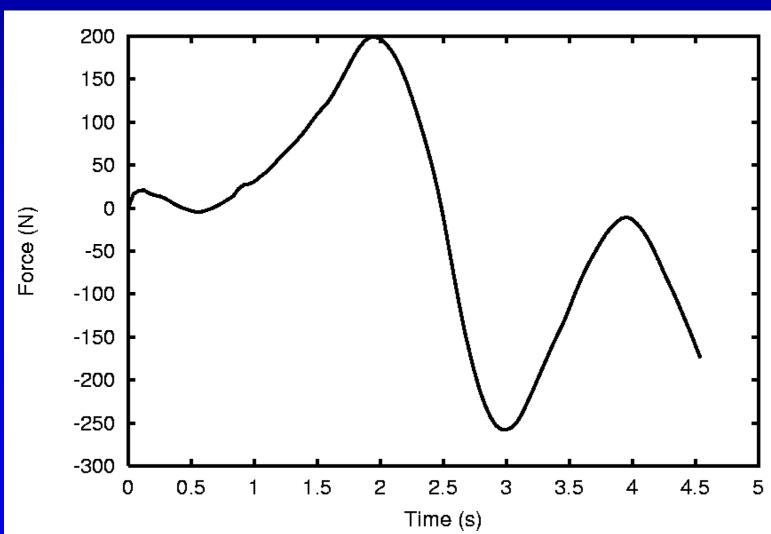


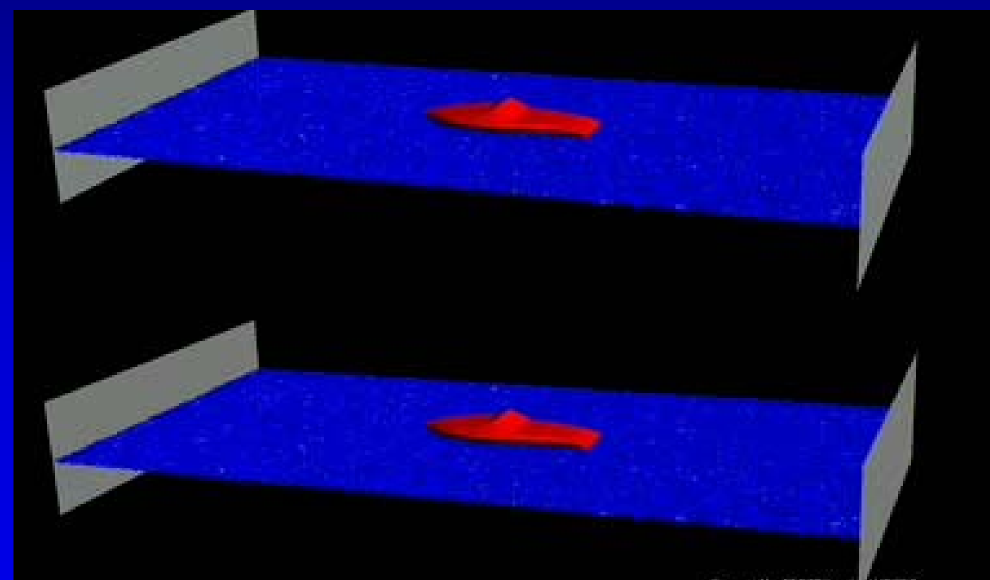


Wave Generator And 6 DOF Application:

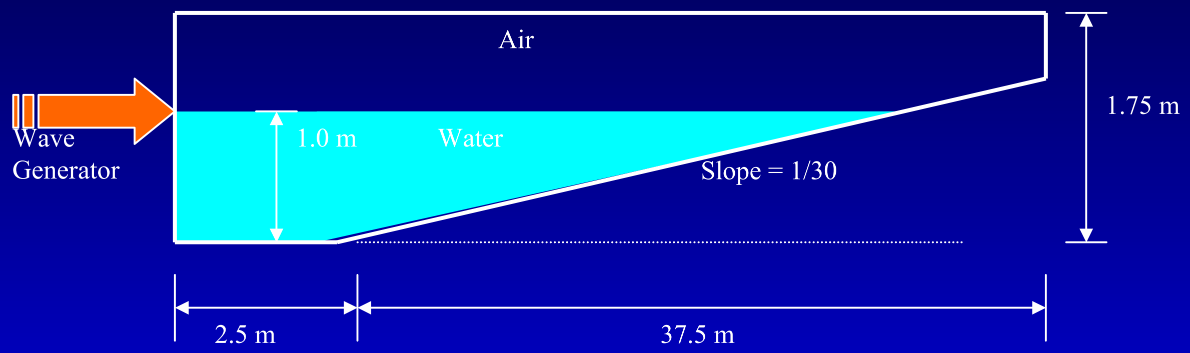


Drifting Boat

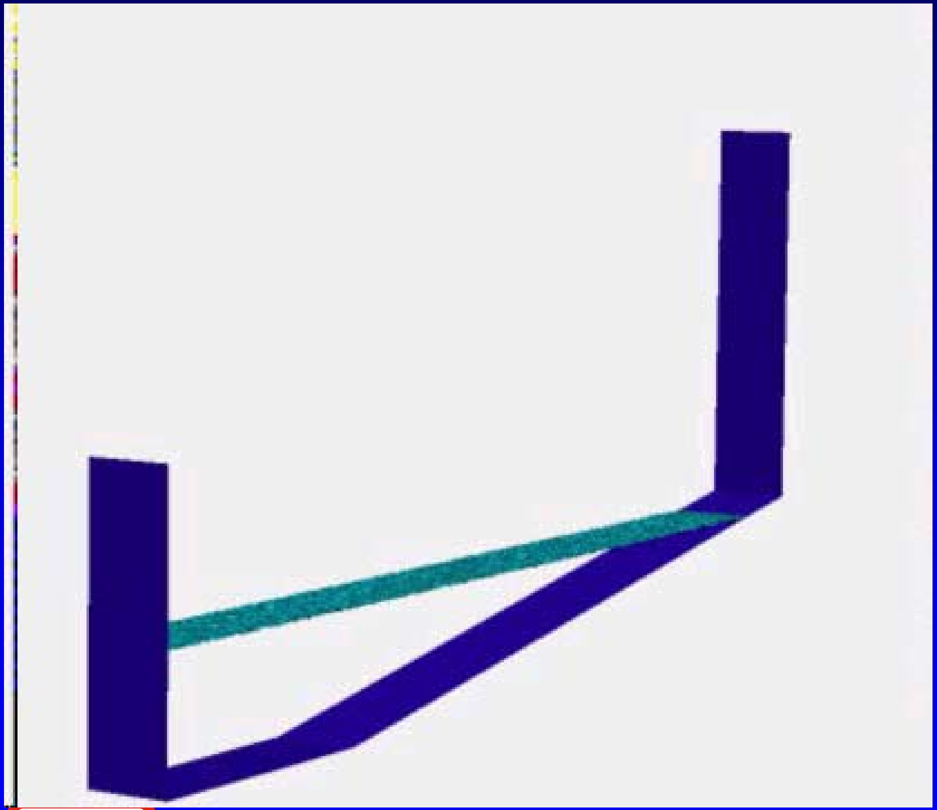


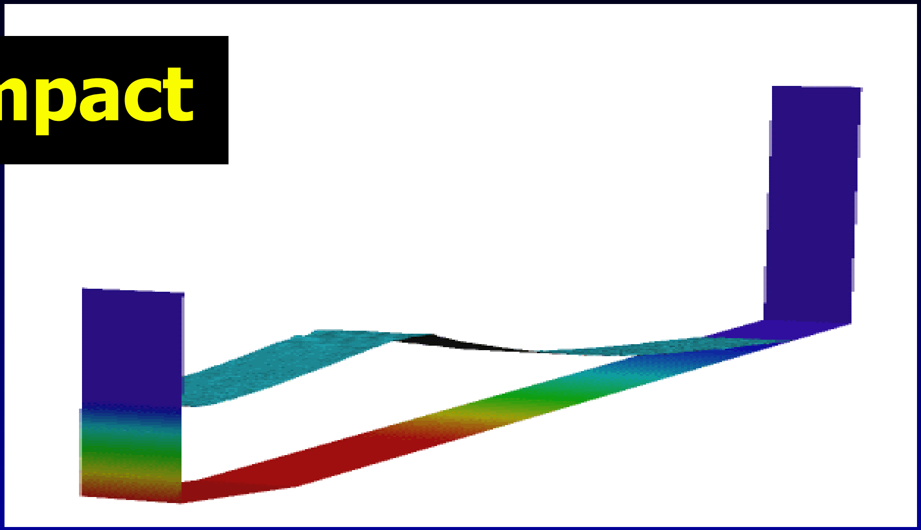


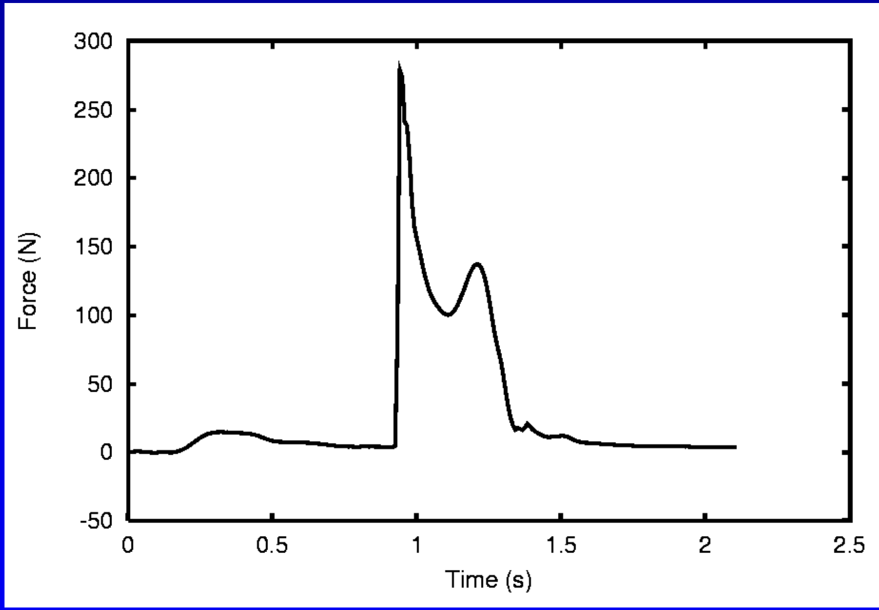
Virtual Laboratory: Wave Generator



3D Application: Wave Impact





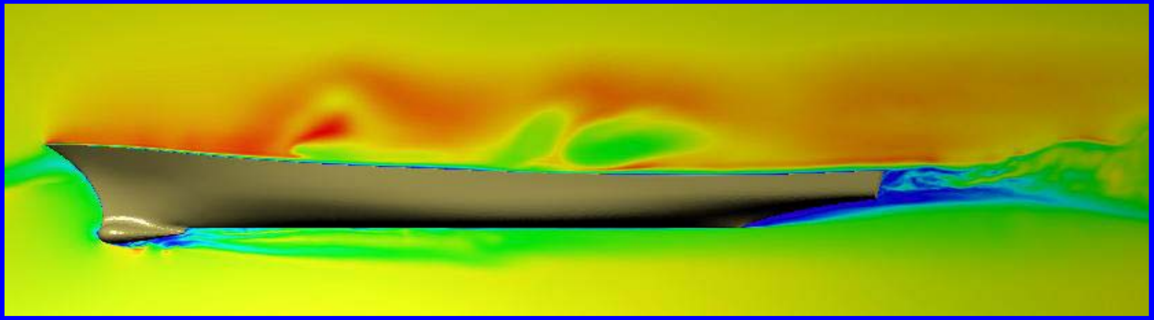


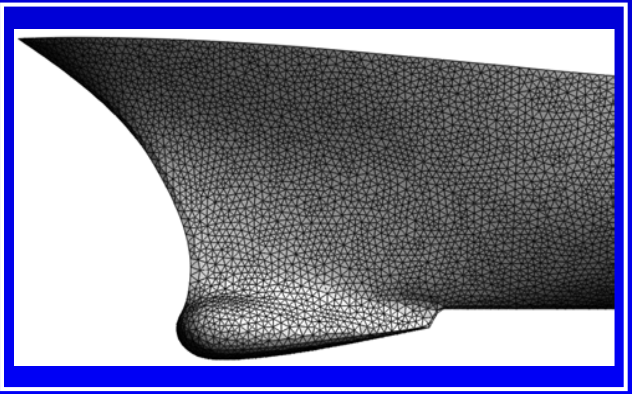
Large-Scale Simulation

Largest Implicit Finite Element Application with Unstructured Mesh

- **One Billion Tetrahedral Elements**
- 875 Million Equations
- 130 Gigaflops Sustained Computation Speed
- Metis Mesh Partitioning
- Parallel Mesh Multiplication
- Remote Visualization

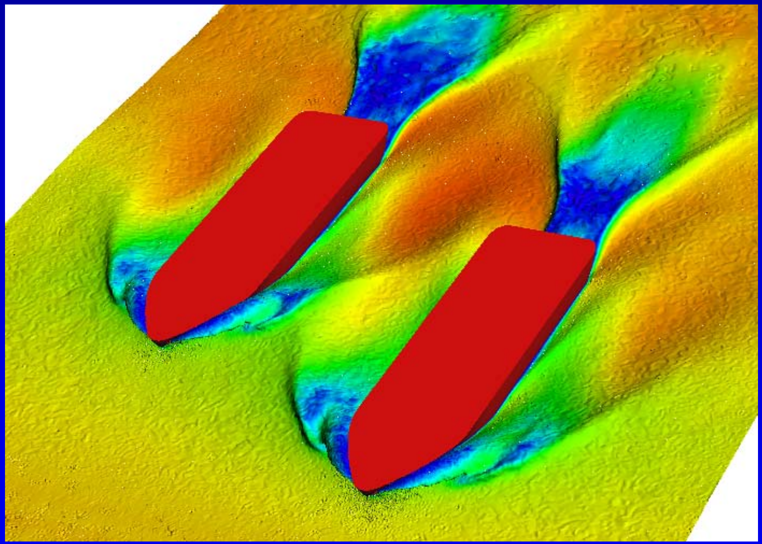
Cray T3E-1200, 1088 Processors,1.3 Teraflops Peak, 557 Gigabytes, World's 7th Fastest Computer

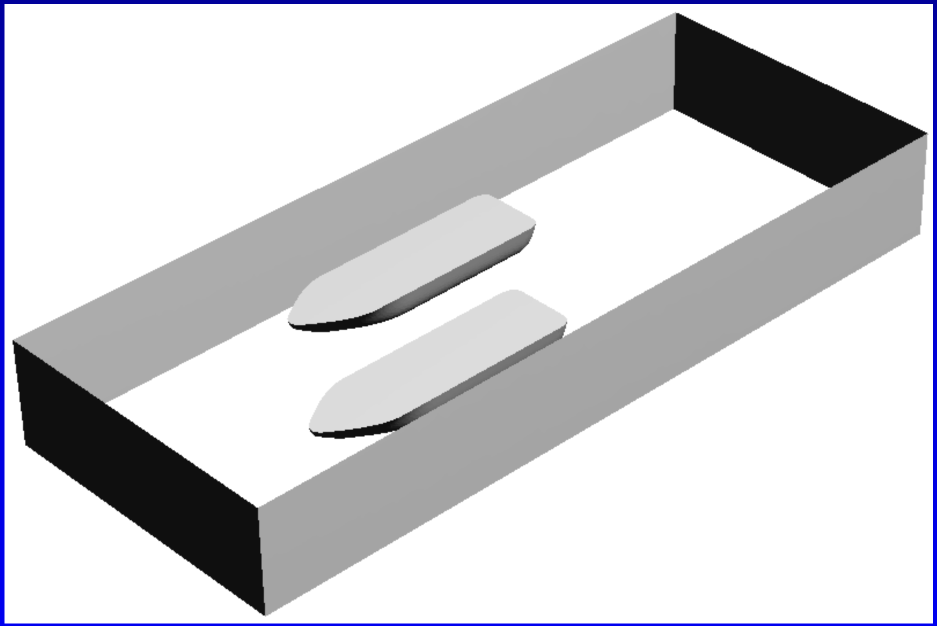




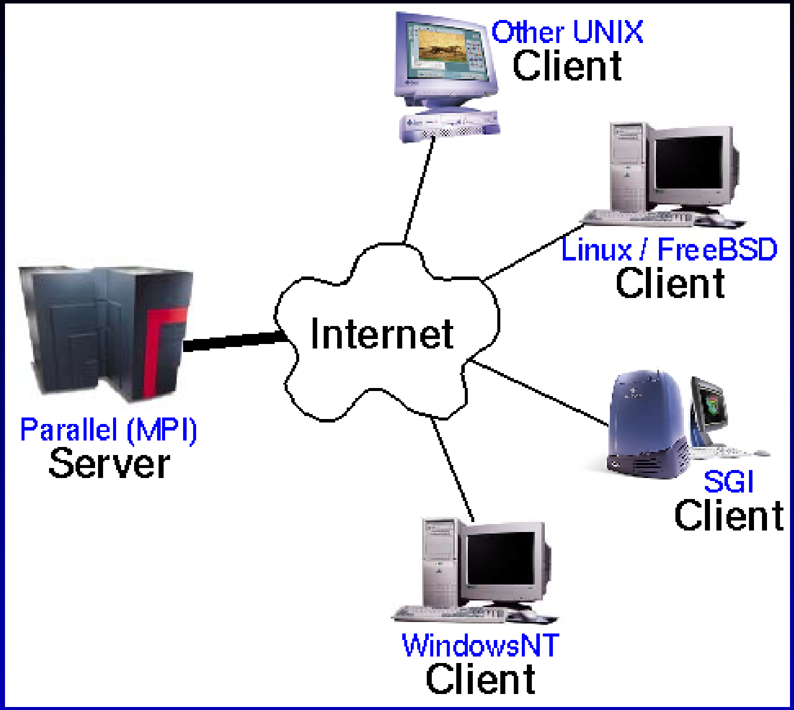
Large Data Set Visualization

- Mesh Information: 68 Gigabytes
- Output for 50 Time Step: 300 Gigabytes
- Total For 50 Time Steps: ~400 Gigabytes

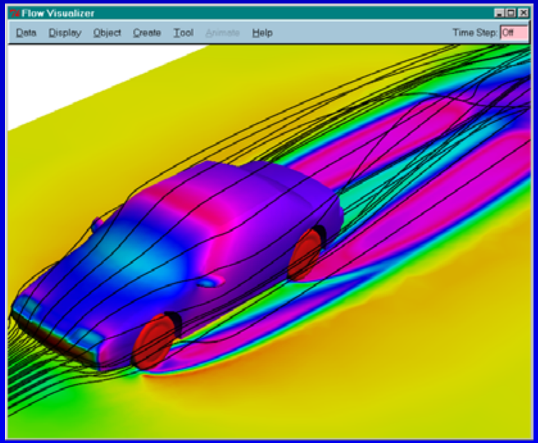




Remote Visualization

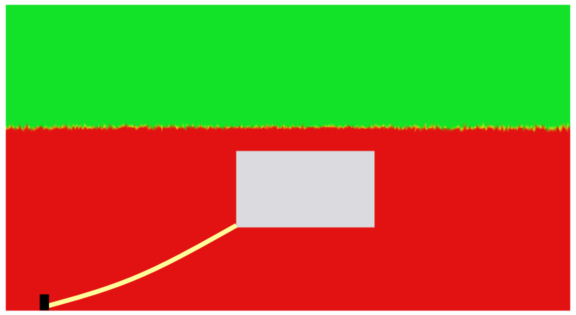


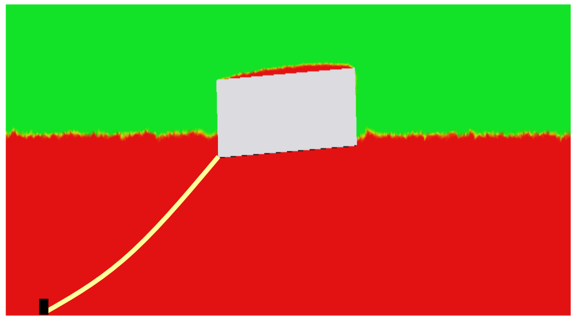
- Server
  - Distributed memory (MPI)
  - Runs where data was generated
  - Handles all data manipulations and geometry



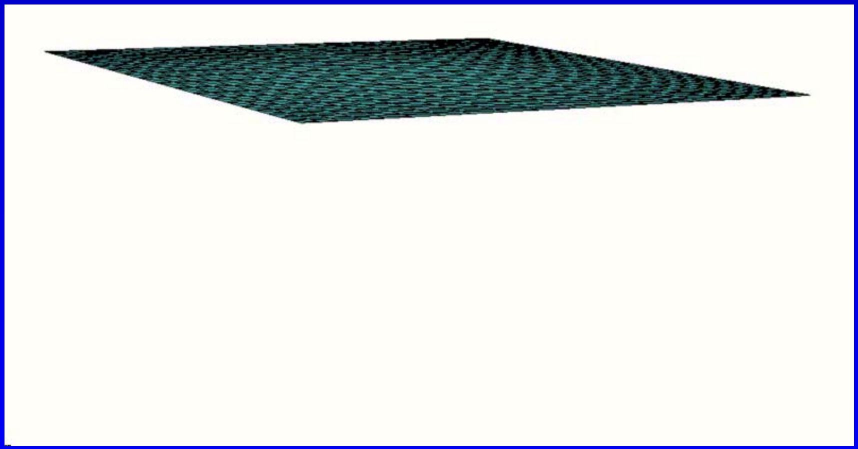
- Local Client
  - Handles user interface and 3D visualization
  - OpenGL, TCL/TK, C, Sockets
  - Low memory

Present Work on Model





- Free surface flow with nonlinear cables
- Absorbing boundaries
- Prescribed water surface or wave generator motion
- Fabrics and flexible structures



Conclusions

- Navier-Stokes model can solve very complex fluid-vessel interaction and fluid-structure interaction
- Ship models need to gridded
- Develop more sophisticated ship-wake-stability model
- Combine ship wakes and wind waves for life cycle analysis